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# Using a combination of industrial and agricultural wastes to manufacture sustainable ultra-high-performance concrete

Ibrahim Y. Hakeem [a], Mohamed Amin [b,c], Ibrahim Saad Agwa [b,d,*], Mahmoud H. Abd-Elrahman [d], Mohammad Farouk Abdelmagied [e]

[a] Department of Civil Engineering, College of Engineering, Najran University, Najran, Saudi Arabia
[b] Civil and Architectural Constructions Department, Faculty of Technology and Education, Suez University, Egypt
[c] Civil Engineering Department, Mansoura High Institute for Engineering and Technology, Mansoura, Egypt
[d] Department of Civil Engineering, El-Arish High Institute for Engineering and Technology, El-Arish, North Sinai, Egypt
[e] Civil Engineering Department, Benha Faculty of Engineering, Benha University, Benha, Egypt

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ABSTRACT

Today, recycling and the use of eco-friendly construction supplies are major concerns for the environment. Concrete is frequently utilized in the engineering and construction sectors. In the past several decades, ultra-high performance concrete (UHPC), characterized by very high mechanical qualities, has emerged as one of the most popular types of concrete. Huge quantities of Ordinary Portland cement (OPC) are often utilized; this increases the price of UHPC, limits its widespread usage in structural applications, produces a substantial quantity of carbon dioxide, and uses a sizable amount of natural resources. It is recommended that other additives be used in lieu of OPC in concrete preparation and that recycled aggregates from a variety of sources be used in place of natural aggregates to make UHPC production more environmentally friendly and economically feasible. This study combines industrial and agricultural waste to create an affordable and sustainable UHPC. For example, glass particles (GP) as a manufacturing byproduct generated by glass waste (GW) are utilized as an alternative for fine aggregate "sand (S)" with substitution ratios of 0 %, 50 %, and 100 %, while wheat straw ash (WSA), as an agricultural byproduct, is utilized as an OPC substitute at varying substitution ratios 0 %, 10 %, 20 %, and 30 %. We conducted and analyzed experiments with 12 mixtures divided into three groups. Several factors are studied, including slump flow, mechanical characteristics, drying shrinkage, high temperature, and microstructural features. Based on the obtained outcomes, boosting the percentage of GP utilized to substitute the S made it more workable. In addition, replacing 20 % of the OPC with WSA and 0 % of the S with GP yielded the best results in terms of mechanical characteristics. Increasing the WSA replacement rate while fixing GP to S substitution level significantly reduced drying shrinkage values. Lastly, the compressive strength ($f_c$) findings of UHPC structural components exposed to elevated temperatures up to 200 °C were enhanced using GP as a replacement for S. In brief, the results of this experimental investigation can contribute well to illustrating the effect of utilizing GP and WSA to manufacture sustainable ultra-high-performance concrete.

*Abbreviations:* UHPC, Ultra-high-performance concrete; GP, Glass particles; GW, Glass waste; WSA, Wheat straw ash; S, Sand; $f_c$, Compressive strength; $f_{sp}$, Splitting tensile strength; $f_f$, Flexural strength; SF, Silica fume; QP, Quartz powder; SP, Superplasticizer; SEM, Scanning electron microscope.

* Corresponding author at: Civil and Architectural Constructions Department, Faculty of Technology and Education, Suez University, Egypt.
*E-mail address:* ibrahim.agwa@suezuniv.edu.eg (I.S. Agwa).

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## 1. Introduction

Reducing waste and ensuring the long-term viability of building materials have become pressing concerns in the environmental community [1]. The construction industry relies heavily on concrete [2,3] and has excellent compressive strength ($f_c$) [4]. In recent decades, one of the most popular concrete types is ultra-high performance concrete (UHPC), defined by extraordinarily outstanding mechanical characteristics and extraordinary endurance [5–8]. It may be deemed a novel building [9–11]. It can potentially be used for a range of highly important objectives [12–16]. UHPC is comprised of high-amount cement, steel fiber, aggregate, a water reducer with a wide range, and very little water [17]. UHPC is created by increasing the concentration of cement material to the greatest extent possible. UHPC combinations have a cement dosage of 900 ~1100 kg/m$^3$ [18], with roughness double or triple times that of ordinary concrete. UHPC's initial cost increased because of its high cement content, restricting its wider use in structural implementations. Also, huge cement content emits a significant amount of $CO_2$, and vast quantities of resources and energy are used, raising concerns about the worldwide environmental impact of UHPC [5,19]. Consequently, substituting cement in concrete preparation with other additives, such as agricultural wastes, and employing industrial wastes for aggregate natural replacement is proposed to make the construction sector more eco-friendly and economically sustainable.

In recent years, agricultural waste materials such as rice husk ashes [20,21], sugarcane bagasse ashes [22–24], palm oil ashes [25], peanut husk ash [26], agro-industrial wastes [27], sesame stalk ash[28], and dust wood ashes [29] have been used as a substitute for cement in recent years. Various research surveys have been completed on these ashes. In contrast, few studies have been conducted on employing other agriculture waste ashes, like wheat straw ash (WSA), used in this study. It has been shown that agricultural ashes have an intense pozzolanic reaction and may be useful as an alternative cement component [30–33]. Because of their broad particle size distribution and pozzolanic capability, they can enhance the interfacial transition zone's microstructure. The viability of using WSA as a constituent in concrete may provide a method for managing those agricultural residues. The world's most widely grown crop is wheat, and Pakistan ranks eighth in yearly production with 27 million tonnes. Pakistan produces a lot of wheat, resulting in many waste wheat straws being made each year [20]. The quantity of wheat straw being produced indicates that around 16 million tons of waste wheat straws are produced annually in Pakistan.

Few studies have looked at WSA as a supplementary cementitious material [21–23]. For example, Bheel, Ibrahim, Adesina, Kennedy and Shar [34] concluded that Using WSA as a substitute for cement harms the slump. Chemical additions are recommended to increase the workability of concrete mixes containing WSA when a higher slump is desired. WSA's integration at up to 10 % cement substitution improved the $f_c$, splitting tensile strength ($f_{sp}$), and flexural strength ($f_f$) by 12 %, 10 %, and 11 %, respectively, in addition to its sustainability benefits. Using 10 % WSA as a substitute for cement was optimal since the strength decreased with increasing content (i.e., over 10 %). The improvement in mechanical characteristics resulting from the partial substitution of cement with WSA was attributable to its capacity to create more reaction products and its reactivity with calcium hydroxide.

Furthermore, to achieve sustainability, industrial waste is used within this trend [35]. Glass waste, which is used as common items, is one of these well-known industrial wastes. It adds considerably to local waste, and the volume of glass trash has increased tremendously in recent years [36,37]. In recent years, Approximately 300 tons of glass waste (GW) have been generated every day on average, according to official statistics [38,39]. Recycled glass is utilized as both coarse and fine particles in concrete because of its approximate density (2.60) and low absorption coefficient, making this one of the most common uses for GW [40]. This is an alternative application for the material. Using natural aggregate contributes to the exhaustion of resources that cannot be maintained indefinitely, such as beaches and quarries. As a result, a multitude of research is offered to highlight the influence of GW application as an alternative for natural aggregate. In accordance with mechanical attributes, Penacho et al. [41] discovered that using 100 % glass particles (GP) instead of S resulted in a reduced $f_c$ after 28 days. Finer GW used in place of S is known to negatively affect mechanical characteristics, especially $f_c$ [42–47]. On the other side, the obtained latest outcomes related to the literate demonstrate that Mardani Aghabaglou et al. [41] and Ali and Al-Tersawy [44], In their research, found that the slump becomes greater as the concentration of alternatives increases. As the authors point out, this is because the fine glass grains are more compact than the coarse S ones. The researchers also found that the dry and wet densities of specimens with higher levels of GW were lower, which makes sense given that glass has a lower unit weight.

### 1.1. Research significance

In this study, an eco-friendly and inexpensive UHPC was created by combining waste products from both industrial and agricultural sources. WSA, an agricultural byproduct, is utilized as a cem substitute at varying substitution ratios (0 %, 10 %, 20 %, and 30 %), whereas GP, an industrial byproduct of GW, is used as a fine aggregate "sand (S)" replacement (0 %, 50 %, and 100 %). To achieve this, twelve mixtures are tested and divided into three groups. Slump flow, mechanical characteristics, drying shrinkage, elevated temperatures, and microstructure are tested. The content of the subsequent sections of this investigation is presented below. Firstly, Section 2 details the experimental work in detail. Secondly, Section 3 offers the obtained results and discussion. Lastly, Section 4 exhibits the conclusion of this manuscript.

## 2. Experimental work

### 2.1. Materials used

#### 2.1.1. Ordinary portland cement (OPC)

In this experimental program, CEM I 52.5 N of OPC was applied. UHPC mixtures include significant amounts of OPC (1000 kg/$m^3$), the same as in earlier experiments [48,49]. OPC characteristics were carried out following BSEN197/1 2011 [50]. Also, these properties are delineated in Table 1.

#### 2.1.2. Wheat straw ash (WSA)

Wheat straws were collected from farmlands in Egypt's El-Menofia region. The WSA is placed in a 600 °C furnace for two hours for heat treatment according to the recommendations in the literature [34,51,52]. Fig. 1 shows the ash of the products obtained after the techniques. The final product of the ashes used was graded by ASTM C618[53]. The chemical properties of ashes are detected by energy-dispersive X-ray (EDX) spectroscopy analysis shown in Table 1.

#### 2.1.3. Silica fume (SF)

The SF employed in this study confirms the specifications in ASTM C1240 [54]. Additionally, SF sized from 0.1 to 1 μm is necessary to produce UHPC [55,56]. SF properties are tabulated in Table 1.

#### 2.1.4. Quartz powder (QP)

The current research adopted QP, and the particle size ranged from 5 to 20 m. Each UHPC mix was developed with QP (less than 10 μm) as a filler [57,58]. Table 1 lists the characteristics of QP.

#### 2.1.5. Fine aggregates

The good qualities are attributable to the mixture's greater homogeneity, achieved by substituting coarse aggregates with S and GP as fine aggregate in UHPC mixes to minimize heterogeneity between the OPC matrix and the aggregate. As a consequence, a thick microstructure forms. This greatly increases UHPC performance [59]. UHPC employs shattered particles GW as a fine aggregate, which is an appropriate replacement for conventional concrete aggregates. It contributes to the conservation of natural resources and the reduction of contamination [44,60]. Crushed GW protects concrete against chloride's destructive effects when used as a fine aggregate.

The GW employed in this study was acquired from several regional makers in Egypt, "Menofia City." Glass that has been used or discarded may be used as a concrete component via the recycling process. Additionally, it has applications in the construction industry. Particle diameters in fine aggregates may be ranged from 0.150 millimeters to about 4.75 millimeters. GW was broken by hand with a hammer, then rolled in an abrasion mill in Los Angeles to get the needed size of GP. The final stage of the crushing cycle included filtering the powder in the lab to maintain the same gradient as the fine natural aggregate. Fine aggregates were tested employing ASTM C33/C33M-18 [61]. The attributes of fine aggregates are outlined in Table 2. The grading curve applied is seen in Fig. 2.

#### 2.1.6. Steel fiber

UHPC's ductility is enhanced with its incorporation of steel fiber. Studies indicate that a dosage of steel fiber (1.5 %) is sufficient [62,63]. So, this ratio is utilized in this research. Table 3 displays the steel fiber characteristics that the manufacturer has given.

**Table 1**
Fine materials' physical and chemical constituents.

| | Ordinary Portland cement | Wheat straw ash | Silica fume | Quartz powder |
|---|---|---|---|---|
| Physical constituents | | | | |
| Specific gravity | 3.15 | 2.38 | 2.15 | 2.57 |
| Initial setting time (min) | 72 | - | - | - |
| Final setting time (min) | 308 | - | - | - |
| Specific area ($cm^2$/gm) | 3530 | 5440 | 20,160 | 5520 |
| Color | Grey | Light Grey | Light Grey | white |
| Chemical constituents (%) | | | | |
| $SiO_2$ | 20.95 | 74.85 | 98.86 | 97.13 |
| $Al_2O_3$ | 4.87 | 3.98 | 0.17 | 0.47 |
| $Fe_2O_3$ | 3.38 | 2.95 | 0.28 | 0.58 |
| CaO | 61.86 | 7.42 | 0.14 | 0.75 |
| MgO | 3.44 | 1.94 | 0.15 | - |
| $SO_3$ | 3.29 | 0.35 | 0.12 | 1.07 |
| $K_2O$ | 0.85 | 4.83 | 0.13 | - |
| $Na_2O$ | 0.74 | 1.75 | 0.15 | - |
| LOI | 0.62 | 1.93 | - | - |


**Fig. 1.** Wheat straw ash preparation technique: a) Wheat plant & wheat, b) Wheat straw, c) Heated at 600 °C for 2 hrs, d) Wheat straw ash.

**Table 2**
Aggregate mechanical and physical characteristics.

| characteristics | Sand | Glass particles |
|---|---|---|
| Specific gravity | 2.66 | 2.62 |
| Density (kg/m$^3$) | 1770 | 1820 |
| Absorption (%) | 0.94 | 0.75 |
| Fine materials (%) | 0.54 | 0.31 |

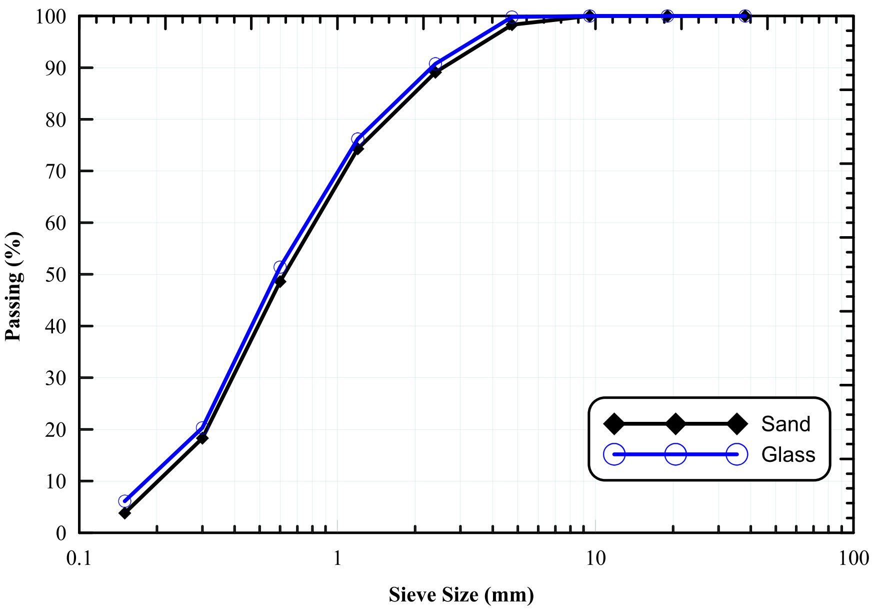



**Fig. 2.** The fine aggregates' gradation curve.

**Table 3**
Characteristics of steel fibers used.

| Length (mm) | Diameter (mm) | Aspect ratio | Tensile strength (MPa) | Elasticity Modulus (GPa) | Density (g/cm$^3$) |
|---|---|---|---|---|---|
| 35 | 0.5 | 70 | 2035 | 188 | 7.80 |

### 2.1.7. *Superplasticizer (SP)*

In this study, SP content was 2.2 % for all UHPC mixtures. The SP requirements are satisfied by ASTM-C-494 Type G [64] and BS EN 934 part 2:2001 [65], which has a specific gravity of 1.08 and a clear liquid appearance. The materials used in this study are seen in Fig. 3.

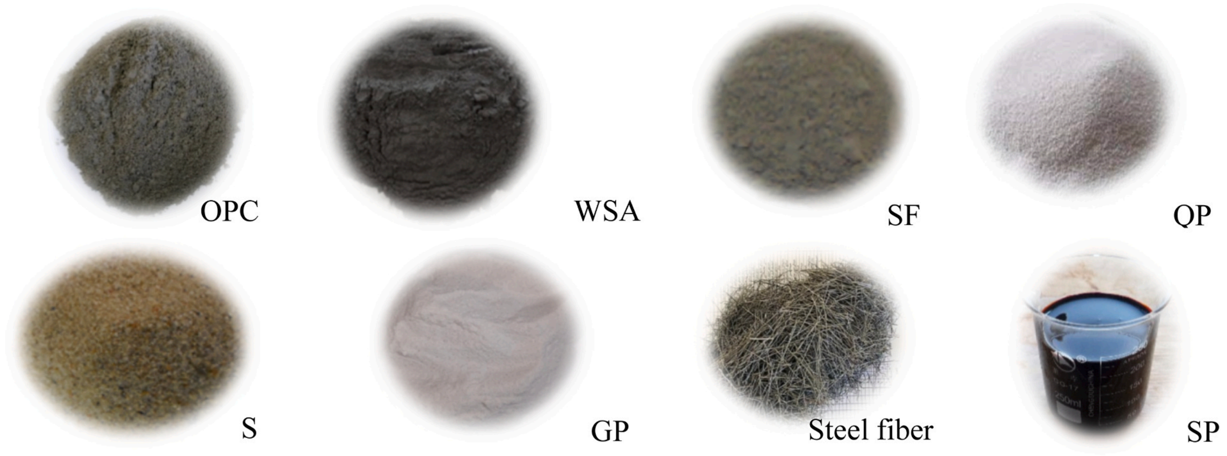



**Fig. 3.** Materials used in this study.

### 2.2. Research methodology

To accomplish the objectives of this research, the experimental work described here was conducted on three primary groups using 12 UHPC mixtures. The mix design procedure utilized in the design of the poured mixes in this research is the absolute volume method. As seen in Table 4, each group comprises four different mixtures, each of which has a single partial replacement from the OPC's content, ranging from 0 % to 30 %. The first group utilized solely 100 % S as fine aggregates with OPC content ranging from 700 to 1000 kg/m$^3$ and substituted WSA for OPC in amounts ranging from 0% to 30 % in UHPC mixtures (100–300 kg/m$^3$). The following groups are the same, except for the second and third groups, which substituted 50 % S + 50 % GP and 100 % GP, respectively. The SF, QP, steel fiber, SP, and water/binder ratios used in the UHPC specimens design are as follows: 200 kg/m$^3$, 150 kg/m$^3$, 117 kg/m$^3$, 26.4 kg/m$^3$, and 0.19, respectively. 3 UHPC groups include two types of fine aggregates (S, GP) and WSA, which act as the pozzolanic material.

When the binder components and fine aggregates were added to a mixer, the mixture was blended for about three minutes or until it was uniform. As the mixture was stirred, the SP was added along with the residual water. After 24 h, samples were poured and stored under cover. The created samples were taken out of the mold and stored in a curing room at 24 ± 2 °C for 24 h, as per ASTM C192[66]. The samples would then be water cured until the appropriate ages for testing.

### 2.3. Test methods

In addition to microstructural analysis, the researched characteristics of UHPC in this study include slump flow, $f_c$, $f_{sp}$, $f_f$, drying shrinkage, and high-temperature analysis. The flow map of the conducted experimental work is presented in Fig. 4. Based on ASTM C-143 [67], the slump flow test assessed the workability of UHPC mixtures. On cube samples 100 × 100×100 mm, the $f_c$ was evaluated at 1, 7, 28, and 91 days, based on BS EN 12390–3 [68]. The test outcomes are the mean of three observations. The 28-day $f_{sp}$ test was identified using ASTM C 496 [69]. At 28 days, three cylindrical samples of 150 × 300 mm of each mixture were prepared for this test. The $f_f$ of UHPC was determined using the technique provided in ASTM C-78 [70]. For $f_f$, 100 × 100×500 mm prism specimens were employed. The drying shrinkage strain experiment followed ASTM C157 / C157M-17) [71] at 1, 3, 7, 14, 21, 28, and 91 days. The

**Table 4**
mix proportions of UHPC.

| Mixture ID | OPC Kg/m$^3$ | SF Kg/m$^3$ | QP Kg/m$^3$ | WSA Kg/m$^3$ | S (%) | GP (%) | Steel Fiber (%) | SP (%) | Water/ binders |
|---|---|---|---|---|---|---|---|---|---|
| WSA0-S100 | 1000 | 200 | 150 | 0 | 100 | 0 | 1.5 | 2.2 | 0.19 |
| WSA10-S100 | 900 | 200 | 150 | 100 | 100 | 0 | 1.5 | 2.2 | 0.19 |
| WSA20-S100 | 800 | 200 | 150 | 200 | 100 | 0 | 1.5 | 2.2 | 0.19 |
| WSA30-S100 | 700 | 200 | 150 | 300 | 100 | 0 | 1.5 | 2.2 | 0.19 |
| WSA0-S50 G50 | 1000 | 200 | 150 | 0 | 50 | 50 | 1.5 | 2.2 | 0.19 |
| WSA10-S50 G50 | 900 | 200 | 150 | 100 | 50 | 50 | 1.5 | 2.2 | 0.19 |
| WSA20-S50 G50 | 800 | 200 | 150 | 200 | 50 | 50 | 1.5 | 2.2 | 0.19 |
| WSA30-S50 G50 | 700 | 200 | 150 | 300 | 50 | 50 | 1.5 | 2.2 | 0.19 |
| WSA0-G100 | 1000 | 200 | 150 | 0 | 0 | 100 | 1.5 | 2.2 | 0.19 |
| WSA10-G100 | 900 | 200 | 150 | 100 | 0 | 100 | 1.5 | 2.2 | 0.19 |
| WSA20-G100 | 800 | 200 | 150 | 200 | 0 | 100 | 1.5 | 2.2 | 0.19 |
| WSA30-G100 | 700 | 200 | 150 | 300 | 0 | 100 | 1.5 | 2.2 | 0.19 |

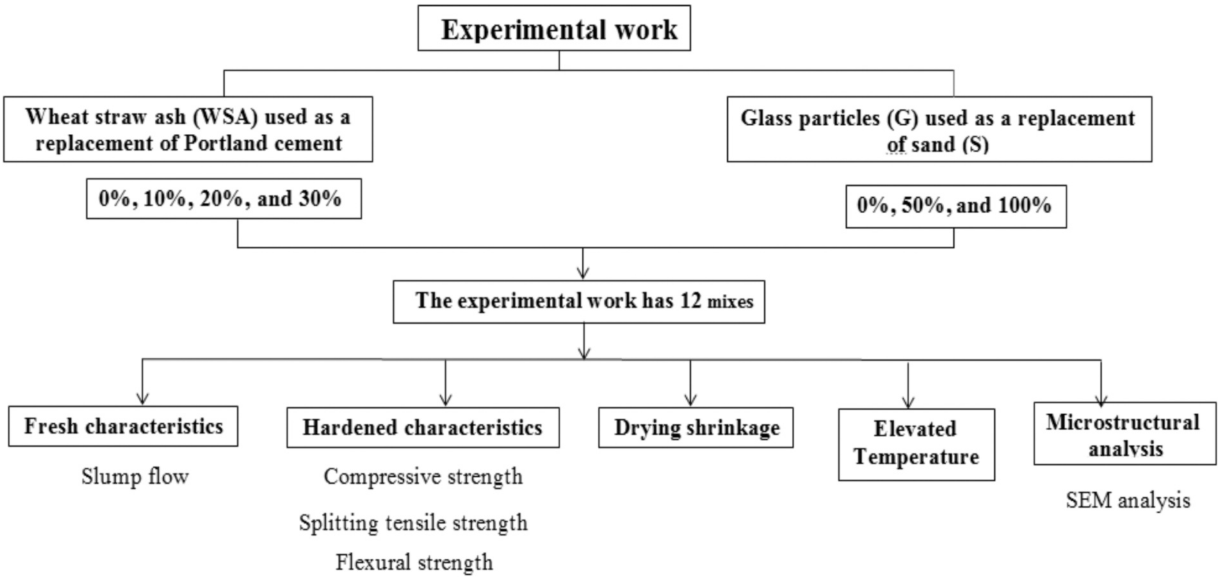



**Fig. 4.** The flow diagram of the carried-out experimental work.

drying shrinkage was evaluated using a 25 × 25×285 mm beam. The samples were heated in a carefully monitored oven at 10 °C/min to study the effect of raised temperatures. Once the required temperature is obtained, it is kept at that level for another two hours. After that, a rate of 1.67 °C/min was employed to lower the furnace's temperature, ensuring no one inside would suffer from any kind of heat shock. Fig. 5 demonstrates the repeated heating and cooling process. The heating technique employed here was similar to that employed by [72–74]. The specimens examined at temperatures (22 °C, 200 °C, 400 °C, 600 °C, and 800 °C) for 2 h. The samples were also evaluated as control at 22 °C. The utilized samples are 100 mm cubes according to EN 2390–3 [75]. In the last step, a scanning electronic microscope (SEM), often known as a "SEM" inspection, was performed on the UHPC samples in order to get information about their microstructure. After being aged for 28 days, the samples were transported to the Science department's laboratory at the University of Alexandria in Egypt, where they were examined to conclude the outcomes.

## 3. Results and discussion

### 3.1. *Slump flow*

Slump flow findings (in terms of flow diameter) for complete UHPC mixes found in the three groups are presented in Fig. 6. It is seen that the flow diameter raised as a consequence of boosting the S replenishment proportion by GP, implying enhanced workability, and so agreeing with [42]. This might result from the glass absorbing a smaller quantity of water than natural S, which raises the amount of

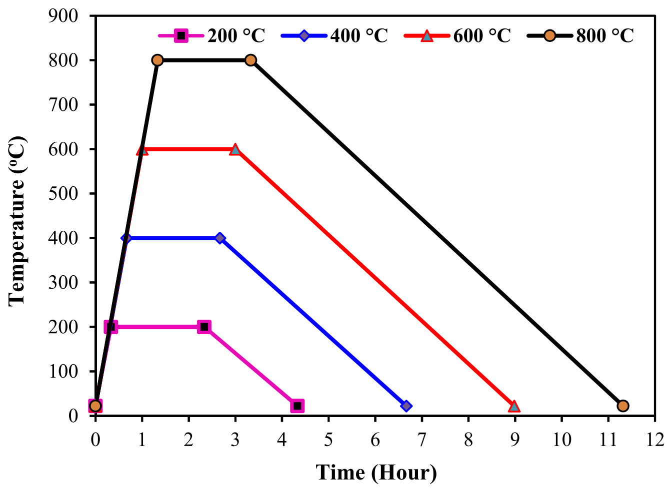



**Fig. 5.** Furnace heating regime.

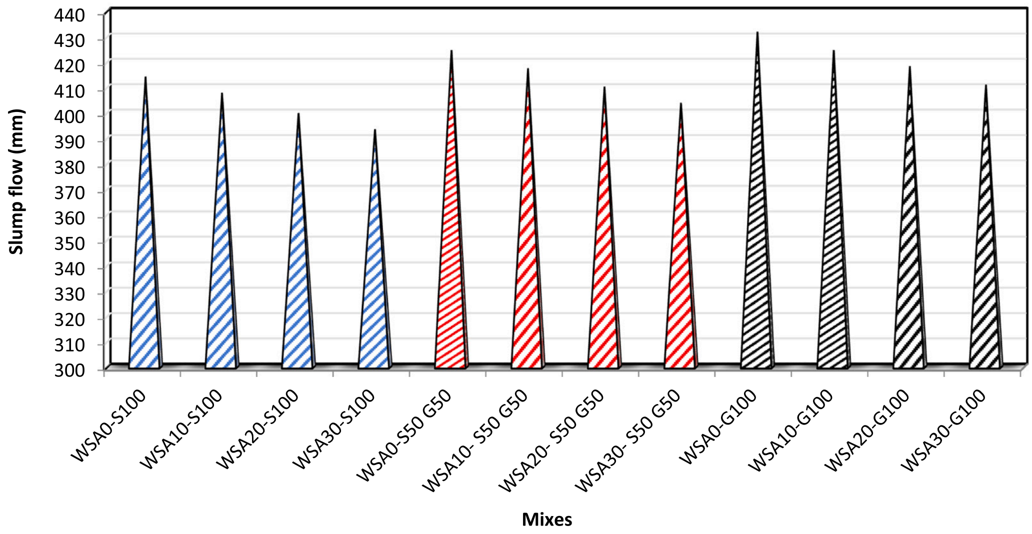



**Fig. 6.** Outcomes of flow diameters of whole casted UHPC mixes.

free water in the mixture. For example, mixes WSA0-S100, WSA0-S50 G50, and WSA S0-G100 had flow diameter sizes of 414.4 mm, 424.8 mm, and 432 mm, respectively. When the rate of S substitution with GP keeps constant, and the quantity of OPC substitution with WSA grows, the diameter of the flow decreases, suggesting decreasing workability. WSA has a smaller molecular size than OPC, with a surface area of 5440 $cm^2$/gm compared to OPC's 3530 $cm^2$/gm; therefore, this might be a reference. Check out the data in Table 1. Large WSA surface areas also contributed to increased water absorption and reduced free water [55,73,76]. The flow diameters of the second group of mixtures ranged from 424.8 mm for the WSA0-S50 G50 mixture to 417.6 mm for the WSA10-S50 G50 mixture, 410.4 mm for the WSA20-S50 G50 mixture, and 404 mm for the WSA30-S50 G50 mixture. The final findings indicated that the WSA0-G100 combination was the most workable (with a flow diameter of 432 mm), while the WSA30-S100 mixture was the least. (with a flow diameter of 393.6 mm).

### 3.2. *Hardened characteristics*

#### 3.2.1. *Compressive strength ($f_c$)*

Fig. 7 exhibits the total achieved $f_c$ findings at various ages; 1, 7, 28, and 91 days of conducted UHPC mixtures. In summary, the findings demonstrate that raising WSA as partial substitutions of OPC from 0 % to 30 % with a constant substitution level of S with GP has an adverse impact on UHPC $f_c$ during the 1-day test age utilized in this study. On the other hand, for the other tests at ages 7, 28,

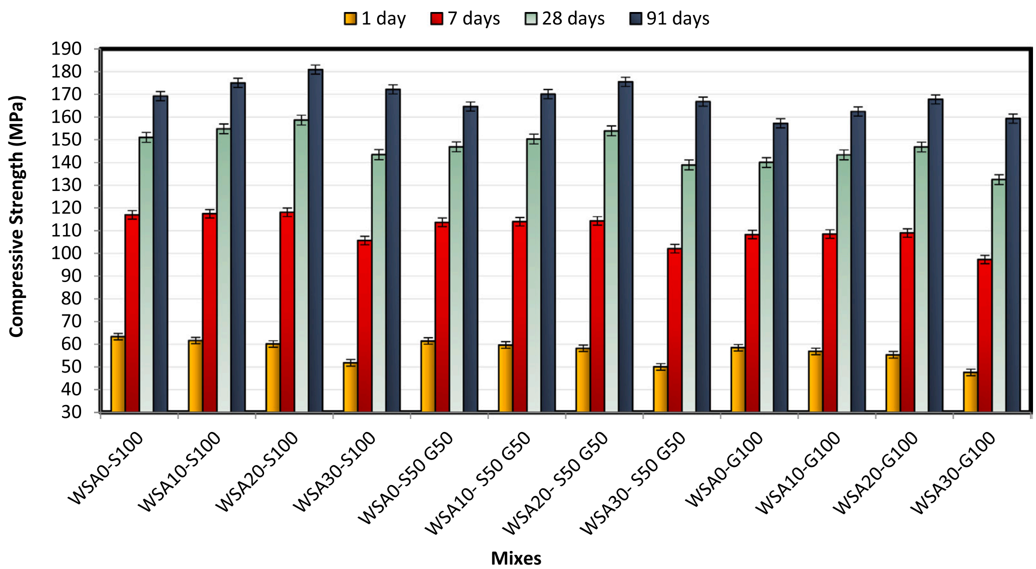



**Fig. 7.** Compressive strength outcomes of all UHPC mixes at various ages.

and 91 days, the $f_c$ was boosted up to a 20 % substitute level before being reduced where the recorded $f_c$ at 1 day when applying WSA as a partial alternative by 0 %, 10 %, 20 %, and 30 % of OPC weight in additional to 0 % substitution of S with GP as example were 63.36, 61.65, 60.12, and 51.84 MPa, respectively. In comparison, the obtained $f_c$ outcomes at 91 days were 169.2, 175.1, 180.9, and 172.2 MPa, respectively. A possible explanation for this is the lengthy curing period necessary to finish the calcium hydroxide reaction (CH). Furthermore, the $f_c$ findings of the first group mixtures at 28 days were 151, 154.8, 158.7, and 143.5 MPa, respectively, while the $f_c$ values of the second group mixtures at the same test age were 146.9, 150.3, 153.9, and 139 MPa, respectively. The $f_c$ findings at 28 days for the 3rd group contained mixes; WSA0-G100, WSA10-G100, WSA20-G100, and WSA30-G100 were 140, 143.4, 146.8, and 132.5 MPa, respectively. According to the above outcomes for each group, the $f_c$ values increased up to a certain level, a 20 % substitution ratio from OPC with WSA, which is observed as the best level to achieve the highest $f_c$ findings; after this level, it reduces; this could be due to many factors, involving the fineness of WSA, which helps in the improved reaction of pozzolanic materials; this is in agreement with [34,77], While it is possible to replace S with GP, it is not recommended to increase the amount of GP in the mixture instead of S. When it is seen that increasing the replacement levels of GP from S results in a reduction in the amount of $f_c$ that is produced, this may suggest that there is a weaker bond between the OPC and glass than there is between natural S and the OPC. One possible explanation is that the GP has a smoother surface than the natural S, reducing the adhesion between it and the OPC paste. This follows the current trend [78,79]. Lastly, the additional $f_c$ data acquired at various ages, including 7 and 91 days, show a tendency consistent with the findings obtained after 28 days.

### *3.2.2. Splitting tensile strength ($f_{sp}$)*

The $f_{sp}$ findings of whole UHPC mixtures that were achieved after 28 days are displayed in Fig. 8. It displayed the relationship between the names of the mixes, which were located on the horizontal axis, and the $f_{sp}$ values, which were located on the vertical axis, in MPa. When the percentage of S remains the same while changing the OPC ratio with WSA, it has been found that $f_{sp}$ levels grow up to 20 % replacement and then fall beyond that point. This is the case in each group. Beyond that point, the $f_{sp}$ values decline. These findings in agreement with [79,80]. For example, in the first group, achieving $f_{sp}$ values of 15.21, 15.66, 16.2, and 14.76 MPa, is accomplished by employing 0 % substitution of GP with S in addition to substituting OPC weight with rates of WSA by 0 %, 10 %, 20 %, and 30 %, respectively.

On the other hand, it was seen that raising substitution levels of GP from S while maintaining a similar substitution level for OPC had a negative impact on $f_{sp}$ findings. This result in accordance with [41,78]. As an example, the outcomes for the $f_{sp}$ of the mixes WSA20-S100, WSA20-S50 G50, and WSA20-G100 were 16.2, 16.02, and 15.57 MPa, respectively. For the final step, the optimal level for improving $f_{sp}$ value is to replace 20 % of OPC S with WSA while performing no replacement of S with GP. In addition, every factor that had a role in producing these outcomes is connected to one of the factors described in the $f_c$ section.

### *3.2.3. Flexural strength ($f_f$)*

The acquired $f_f$ findings of full casted UHPC mixtures are outlined in Fig. 9, which represents the impact of substituting OPC with WSA and S with GP on the $f_f$ outcomes evaluated after 28 days. $f_f$ findings were calculated after 28 days. The first group found that the WSA20-S100 mixture had the greatest $f_f$ value, 23.13 MPa. This was a rise of approximately 6.20 % when contrasted with the reference mix in this group, "WSA0-S100." On the other hand, the "WSA30-S100" mixture had the lowest $f_f$ value, which was 21.06 MPa. This dropped approximately 3.30 % when contrasted with the same control mixture. It was found that the mixture "WSA20-S100" had the highest $f_f$ value at the casted UHPC 12 mixes, with 23.13 MPa, while the mixture "WSA30-G100" had the lowest value, with 19.98 MPa.

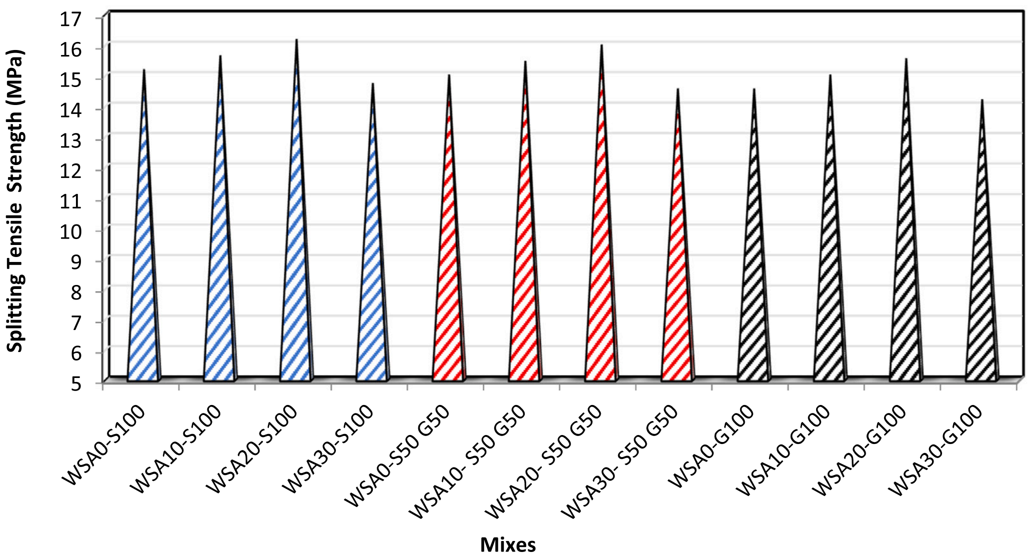



**Fig. 8.** Splitting tensile strength outcomes of conducted UHPC mixes at 28 days.

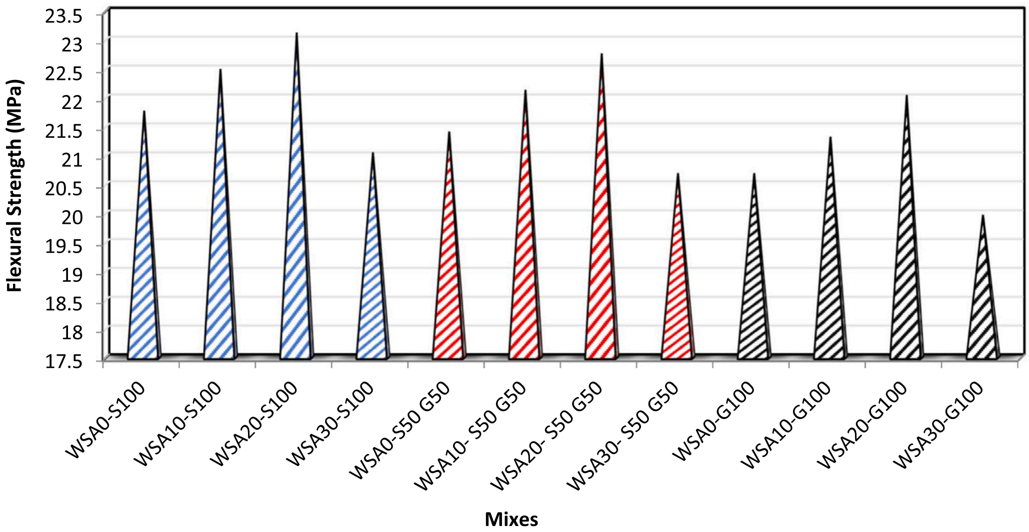



**Fig. 9.** Flexural strength outcomes of conducted UHPC mixes at 28 days.

This indicates that the best dose to replace OPC with WSA is 20 %, and the optimal dosage to replace S with GP is 0 %. This result follows many investigations [78,79,81]. The scientific clarification may refer to the reasons presented in the $f_c$ paragraph.

### 3.3. Drying shrinkage

Drying shrinkage outcomes of whole UHPC mixtures at various ages; 1 day, 3, 7, 14, 21, 28, and 91 days are presented in Fig. 10. Where Fig. 10 illustrates the relationship between the test of age in the horizontal axis in days with the drying shrinkage values in microstrain in the vertical axis. It is clear that, for each mix, there is an incremental relationship between drying shrinkage values and age tests. For example, for mixture WSA0-S100, the drying shrinkage values were 127.8, 163.8, 211.5, 295.2, 351, 405, and 445 microstrain at the test of ages 1, 3, 7, 14, 21, 28, and 91 days, respectively. Furthermore, it is discovered that raising the substitution level of WSA instead of OPC at a constant substitution level of GP to S makes a notable drop in drying shrinkage findings. In contrast, for clarification, the acquired outcomes for drying shrinkage of the third group mixtures at 28 days were 390, 374, 360, and 347 microstrains for mixtures WSA0-G100, WSA10-G100, WSA20-G100, and WSA30-G100, respectively. That may refer to the absorption of the water of OPC molecules being higher than WSA particles and also may refer to the difference in their surface shape [77,79]. Furthermore, in this trend, raising the substitution rate of GP instead of S at a constant rate of WSA to OPC makes a notable reduction in drying shrinkage value. For example, the drying shrinkage values at 28 days for mixtures WSA0-S100, WSA0-S50G50, and WSA0-G100 were 405, 396, and 390 microstrains, respectively. These findings might be referred to as S having a greater water absorption (%) value than GP, where S and GP had water absorption values of 0.94 and 0.75, respectively. "see Table 2". These findings are in agreement with [82,83].

### 3.4. Elevated temperature

Fig. 11 illustrates the outcomes of the $f_c$ at 28 days due to exposing the UHPC samples to elevated temperatures; 200 °C, 400 °C, 600 °C, and 800 °C for 2 h compared with the obtained $f_c$ values at room temperature (22 °C). Fig. 11 demonstrates the relation between $f_c$ findings at the vertical axis with various temperatures at the horizontal axis, while Fig. 12 shows the % decrease in $f_c$ of the concrete samples. The $f_c$ values for whole mixes dramatically improved when heated to 200 °C, which may be associated with the dry hardening and continuing hydration of the hydrated cement grains [84,85]. These results are in agreement with [86,87]. Also, due to increasing the substitution level of OPC with WSA at a constant replacement level of S with GP or vice versa, the percentage of increase in $f_c$ reduced gradually. For clarification the percentage of increase in $f_c$ at 200 °C for mixes; WSA0-S100, WSA10-S100, WSA20-S100, and WSA30-S100 were 4.53 %, 4.30 %, 4.19 %, and 4.2 %, respectively and the percentage of increase in $f_c$ at 200 °C for mixes WSA0-S100, WSA0-S50 G50, and WSA0-G100 were 4.5 3%, 4.22 %, and 3.98 %. On the contrary, at high elevated temperatures; 400 °C, 600 °C, and 800 °C, it is discovered that there is a remarkable reduction in $f_c$ values compared with these results obtained at 22 °C, and this may refer to the converted calcium hydroxide to calcium silicate hydrate due to the effect of high temperatures [88,89]. In addition, for each mix, it is noticed that increasing the temperature resulted in a remarkable decrease in $f_c$. In contrast, for mixture WSA0-G100, for example, the $f_c$ values at temperatures 400 °C, 600 °C, and 800 °C were 115.83, 74.52, and 39.24 MPa. These results are in accordance with [57,90,91]. Furthermore, due to boosting the substitution level of OPC with WSA at a constant substitution rate of S with GP or vice versa, the percentage of reduction in $f_c$ values reduced gradually. For example, at 800 °C for mixtures; WSA0-S100, WSA10-S100, WSA20-S100, and WSA30-S100 have percentages of reduction 74.31 %, 71.97 %, 68.17 %, and 67.00 %, respectively and for mixes WSA0-S100, WSA0-S50G50, and WSA0-G100 the percentages of reduction were 74.31 %, 72.97 %, and 71.97 %,

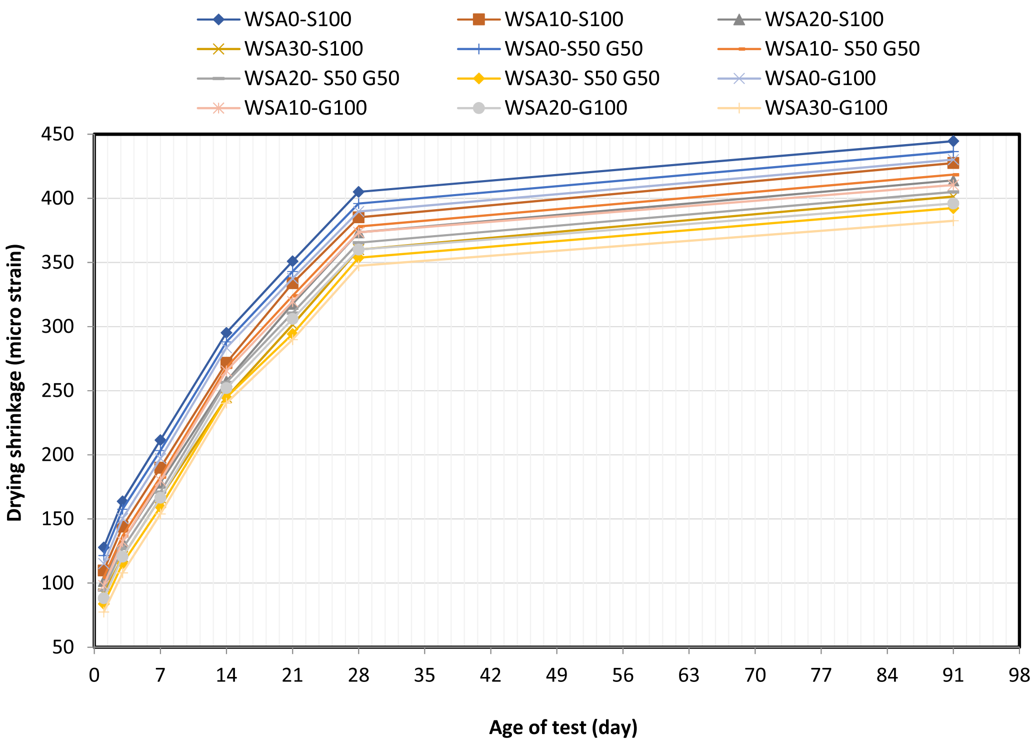



**Fig. 10.** Drying shrinkage outcomes of UHPC mixtures at different ages.

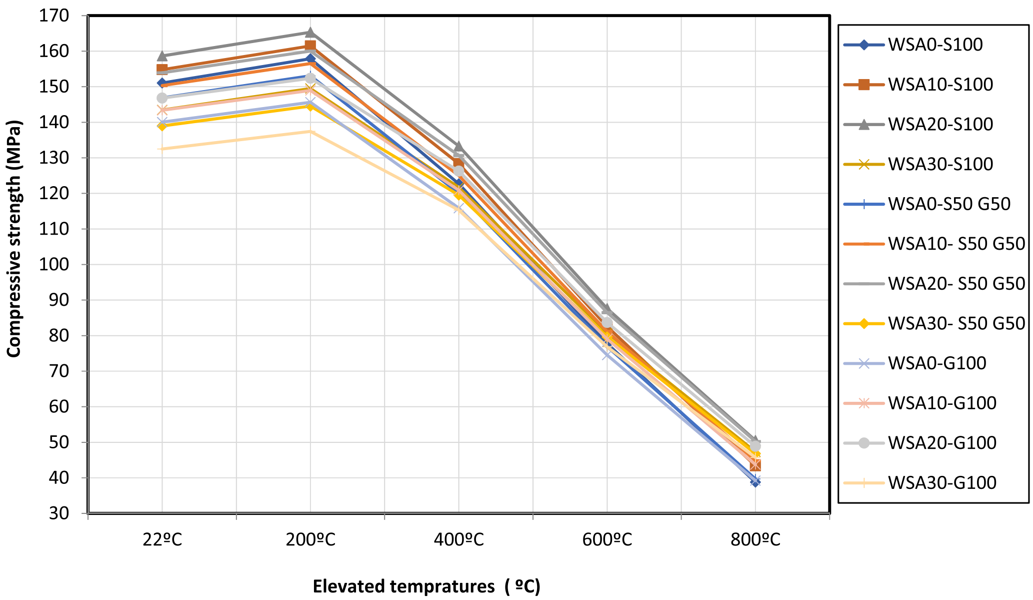
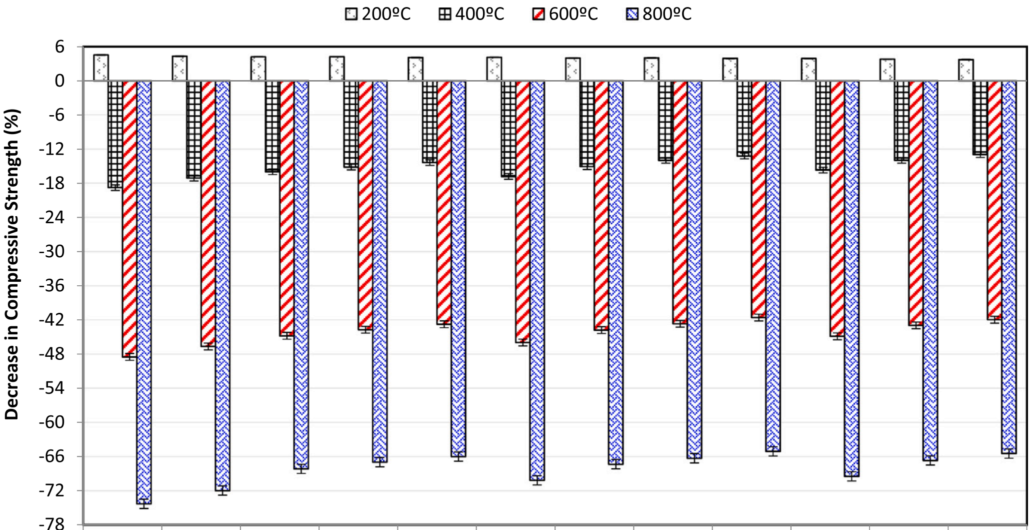



**Fig. 11.** The relationship between compressive strength with various temperatures.

respectively. In the end, it is concluded that it is preferable to use GW in concrete structures subjected to high elevated temperatures as a replacement for OPC with WSA or for S with GP or both of them.

### *3.5. Microstructure*

The SEM pictures in Fig. 13a-d illustrate the microstructure morphology of the UHPC samples WSA0-S100, WSA10-S100, WSA20-S100, and WSA30-S100. The micrographs of WSA10-S100, WSA20-S100, and WSA30-S100 (see Fig. 13b, c, and d) seem to be more




| | WSA0-S100 | WSA10-S100 | WSA20-S100 | WSA30-S100 | WSA0-S50 G50 | WSA10-S50 G50 | WSA20-S50 G50 | WSA30-S50 G50 | WSA0-G100 | WSA10-G100 | WSA20-G100 | WSA30-G100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200ºC | 4.529201 | 4.302326 | 4.197391 | 4.203262 | 4.10596 | 4.131737 | 3.976608 | 4.015544 | 3.906785 | 3.892028 | 3.801349 | 3.736413 |
| 400ºC | -18.7723 | -17.093 | -15.9955 | -15.1819 | -14.3709 | -16.8263 | -15.0877 | -13.9896 | -13.2282 | -15.6937 | -13.9792 | -12.9755 |
| 600ºC | -48.5101 | -46.686 | -44.81 | -43.7265 | -42.7815 | -45.988 | -43.8012 | -42.6813 | -41.6038 | -44.8839 | -42.9798 | -41.9837 |
| 800ºC | -74.3147 | -71.9767 | -68.1792 | -67.0013 | -66.0265 | -70.1796 | -67.3684 | -66.3212 | -65.1131 | -69.4915 | -66.7075 | -65.4891 |

Mixes

**Fig. 12.** Percentage decrease in compressive strength (%) at 28 days.

dense and compacted than the erratic and wavy micrograph of WSA0-S100 (see Fig. 13a), which is distinguished by its absence of response specimen and interfacial cracks. These flaws indicate inadequate hydration and flakiness in the microstructure. When 20 % of the OPC was replaced with S100, the best mixes with the best microstructure (thick, with no gaps or cracks) had the greatest mechanical qualities. This was due to the mixture's hydraulic ability, which allowed it to interact with $Ca(OH)_2$ to form more C-S-H gel. The thick microstructure caused by the pozzolanic material is seen in the SEM image. The pozzolanic material in the mix has a better microstructure than the control mix [49,73,76,92].

## 4. Conclusions

This study seeks to create an ecologically friendly and economically sustainable UHPC by substituting GP as an alternative for S with substitution ratios of 0 %, 50 %, and 100 %, while WSA, as an agricultural byproduct is utilized as an OPC substitute at varying substitution ratios 0 %, 10 %, 20 %, and 30 %. Twelve mixes are performed and evaluated experimentally to accomplish this purpose. The features of fresh, hardened, drying shrinkage, higher temperature, and microstructure are all examined. The following conclusions were reached:

- UHPC becomes more workable when GP boosts substitute degree S. When the ratio of S to GP in the substitute process remains the same, boosting the ratio of OPC to WSA reduces the workability of UHPC.
- To make an affordable and sustainable UHPC with excellent mechanical characteristics, the best replacement rates for OPC with WSA and S with GP are 20 % and 0 %, respectively.
- Raising WSA in UHPC as an alternate for OPC from 0 % to 30 % with a constant substitution level of S to GP has an adverse impact on UHPC compressive strength over a one-day test. On the other hand, for the other test, at ages 7, 28, and 91 days, the compressive strength enhanced up to 20 % replacement ratio and then dropped.
- The highest observed values for compressive strength, splitting tensile strength, and flexural strength at 28 days for all casted mixes of UHPC were 176.3 MPa, 18 MPa, and 25.7 MPa, respectively, when 20 % OPC substitution with WSA and 0 % S substitution with GP is adopted.
- The drying shrinkage measurements were drastically reduced when the substitution level of WSA was increased in lieu of OPC at a constant replacement level of GP to S. Drying shrinkage values are greatly reduced when GP is substituted for S at a constant replacement rate of WSA to OPC.
- Utilizing GP as a substitution for S in UHPC structural elements exposed to elevated temperatures up to 200 °C positively affected the compressive strength outcomes.

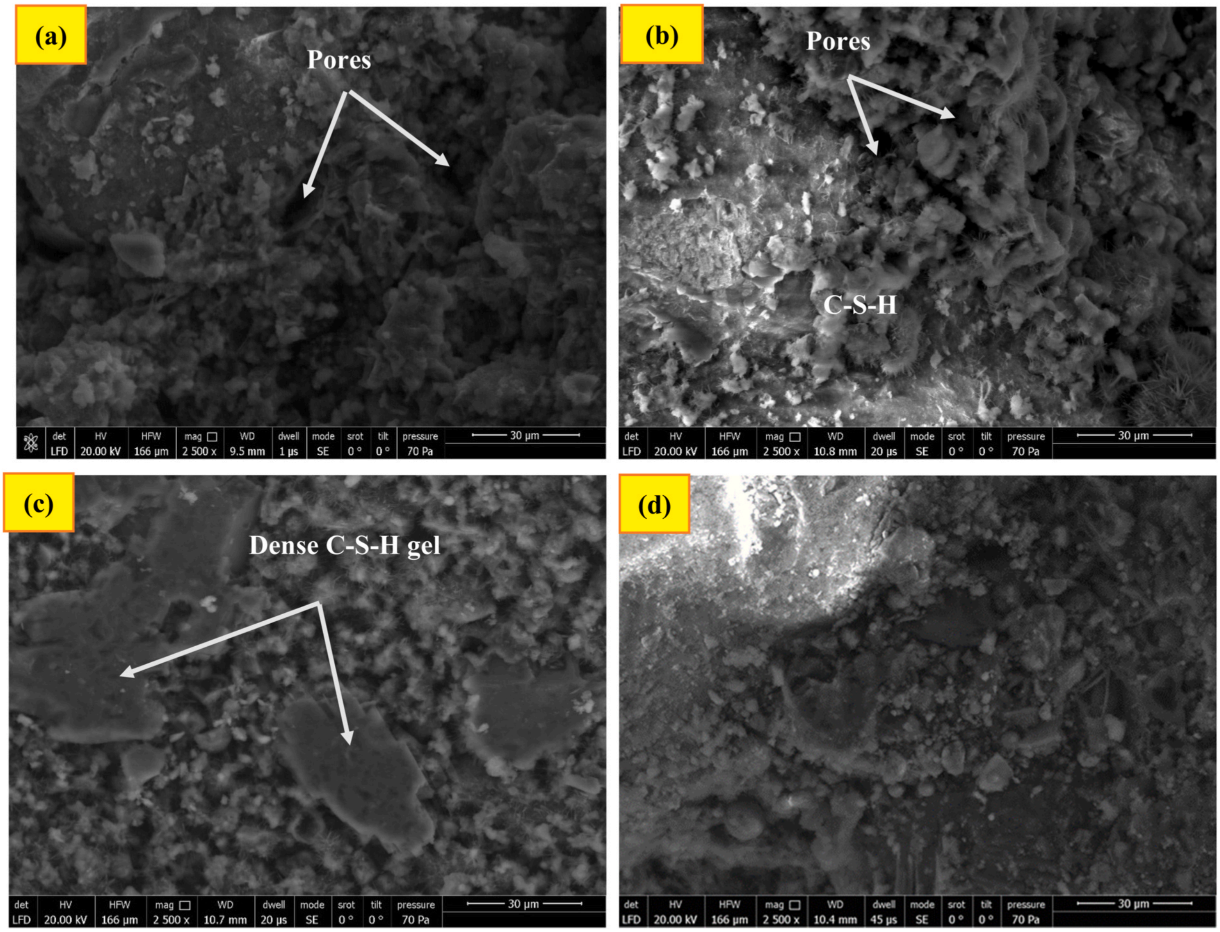



**Fig. 13.** Micrographs of SEM of mixes a) WSA0-S100, b) WSA10-S100, c) WSA20-S100, and d) WSA30-S100.

## 5. Future recommendations

It is advised to conduct experimental and numerical studies on the structural behavior of various UHPC structural elements, including GP and WSA, under static or cyclic loads. We are examining the effects of combining G and WSA on the mechanical and durability properties of different kinds of concrete.

## CRediT authorship contribution statement

All authors contributed equally to conduct this research.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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